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**Neutrinos, Cosmology and Astrophysics<sup>a</sup>**

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We review bounds on neutrino properties, in particular on their masses, coming mostly from cosmology, and also from astrophysics.

Excluding laboratory experiments looking for neutrino oscillations and observations of solar and atmospheric neutrinos (which have been covered by other talks in this conference), most of our knowledge of neutrinos comes from direct mass searches, cosmology and astrophysics. We will deal with these three areas in this order, concentrating our attention mostly on cosmological bounds. These come from data on the content, expansion rate and lifetime of the Universe, the spectrum and anisotropies of the Cosmic Microwave Background Radiation (CMBR), the large-scale structure (LSS) of the Universe and the primordial abundance of the light elements (at present mostly from deuterium) produced during nucleosynthesis (NS) in the early Universe. There are lots of quality data in all these areas. We are entering into the “precision era” of cosmology, when most relevant cosmological parameters will become known to a few percent.

**1 Direct Neutrino Mass Searches**

From experiments we know that  $m_{\nu_e} < \text{few eV}$ . Even if “formal” upper limits of 5 eV (95% C.L.)<sup>1</sup> and 1.7 eV (95% C.L.)<sup>2</sup> have been given in 1998, they are obtained with negative measured square masses, what points to a systematic error. In fact the Particle Data Book gives an upper bound of 15 eV<sup>3</sup>. The bounds on the effective Majorana  $\nu_e$  mass from  $\beta\beta\nu$  decays are of about 1 eV. The Heidelberg-Moscow  $^{76}\text{Ge}$  experiment quoted an upper bound of 0.2 eV<sup>4</sup>, but there are still uncertainties related to the evaluations of the nuclear form factors involved. There has been no recent change in the upper bound of the  $\nu_\mu$  mass,  $m_{\nu_\mu} < 0.17 \text{ MeV}$ <sup>3</sup>, while for  $\nu_\tau$  a preliminary analysis of data from LEP, combining results of ALEPH and OPAL gives  $m_{\nu_e} < 15 \text{ MeV}$  (95% C.L.)<sup>5</sup>. ALEPH and OPAL separately quoted upper bounds of 18.2 MeV (95%

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C.L.) and 27.6 MeV (95% C.L.) respectively, while new results of CLEO II give  $m_{\nu_\tau} < 30$  MeV (95% C.L.)<sup>6</sup>.

Better bounds than these are derived from cosmological arguments if neutrinos are stable, and, if neutrinos are unstable, cosmology and astrophysics give bounds on their lifetimes and decay modes.

## 2 Expansion, Age and Content of the Universe.

The Hot Big Bang (BB), the standard model of cosmology, establishes that the Universe is homogeneous, isotropic and expanding from a state of extremely high temperature  $T$  and density  $\rho$ . The Hubble parameter  $H$  (constant in space but not in time) provides the proportionality between the velocity of recession  $v$  of faraway objects and their relative distance  $d$ ,  $v = Hd$  and  $H = h$  100 km/sec Mpc. Most observational determination are converging to  $h = 0.65 \pm 0.15$ <sup>7</sup> (for example,  $h = 0.67 \pm 0.12$  comes from type Ia Supernovae<sup>7</sup> while  $0.72 \pm 0.17$  comes from combining cepheids studies and other methods<sup>8</sup>), for the present value of the expansion parameter. The lifetime of the Universe is counted from the moment the expansion started, taken to be  $t = 0$ . The cooling of white dwarfs provides a lower bound to the present age of the Universe of  $t_o > 10$  Gyr<sup>9</sup> and the age of the oldest globular clusters gives  $t_o = 13 - 25$  Gyr ( $t_o = 11.5 \pm 1.3$  Gyr<sup>10</sup>, plus 1-2 Gyr for the formation of the galaxy where the globular cluster is. The expansion rate, lifetime and the content of the Universe are not independent. In fact,  $Ht_o = (h/0.75)(t_o/13$  Gyr) is a function of the densities of matter, radiation and vacuum in the Universe. For an empty Universe  $Ht_o = 1$ . The gravitational attraction of matter and radiation slows down the expansion, so that  $Ht_o < 1$  in a matter or radiation dominated Universe. In a vacuum dominated Universe  $Ht_o > 1$  instead, because gravitation is repulsive. In synthesis, a larger  $H$  implies a shorter  $t_o$  and decreasing the matter or radiation content or increasing the vacuum content of the Universe makes  $t_o$  longer.

Densities  $\rho_i$  are usually given in units of the density of a spatially flat Universe, the critical density  $\rho_c = 10.5 h^2$  (keV/cm)<sup>3</sup> =  $1.88 \cdot 10^{-29} h^2$  (g/cm<sup>3</sup>) as  $\Omega_i = \rho_i/\rho_c$ . We call  $\rho_r$ , the density of radiation (photons and other relativistic particles) and  $\rho_m$  the density matter (non-relativistic particles). We will call here  $\Omega_o = \Omega_m + \Omega_r$ . The vacuum energy provides a cosmological constant  $\Lambda$ , such that  $\rho_{vac} = \Lambda/8\pi G = \rho_\Lambda$ . In our notation the total density of the Universe is  $\Omega = \Omega_o + \Omega_\Lambda$ . Matter is much more abundant than radiation at present, thus  $\Omega_o \simeq \Omega_m$ . For a flat matter dominated Universe,  $Ht_o = 2/3$ . This means (using the relation given above) that  $t_o \geq 13$  Gyr (necessary to accomodate globular clusters) requires  $h \leq 0.50$ , a very low value of  $h$ . Even

using the absolute lower bound  $t_o \geq 10$  Gyr, we obtain  $h \leq 0.65$ , still values of  $h$  lower than many present determinations. If  $h$  is actually larger than 0.65, then we live in a Universe with a non-zero cosmological constant or open or both. This tension between  $h$  and  $t_o$  was until recently called the “age crisis”, but this is not called a “crisis” any longer.

One speaks of a “crisis” only when a paradigm is challenged. This paradigm was that of a flat matter dominated Universe with  $\Lambda = 0$ , until recently the model preferred by most cosmologists due to its simplicity and aesthetic appeal. This paradigm has now been changed, mostly by the Type Ia Supernovae (SN) data, which point to a non-zero value of  $\Lambda$ , and, to a lesser extent, by data on the LSS of the Universe, which suggests  $\Omega_m < 1$ . Type Ia SN are white dwarfs which accrete mass from a companion star and explode when reaching the Chandrasekar limit of about 1.4 solar masses, i.e. the maximum mass that can be supported by the pressure of degenerate electrons. Two different groups<sup>11 12</sup> using Type Ia SN as “calibrated” candles (i.e. objects of known intrinsic luminosity) measured the curvature of the relation between distances and velocities (of which the linear term is given by the present value of the Hubble parameter  $H$ ). Recession velocities are actually translated into redshifts  $z$ . Thus, distances  $d$  are given by  $d = H^{-1}[z + O(z^2)]$ . At  $z \simeq 0.5$ , where most of the SN used are, the coefficient of the  $z^2$  term depends on the linear combination  $\Omega_\Lambda - \Omega_m$ <sup>13</sup>, and, in fact, the confidence region given by both groups<sup>11 12</sup> lies along the line  $\Omega_\Lambda - \Omega_m \simeq 0.5$ , in the  $(\Omega_m, \Omega_\Lambda)$  plane. With 42 high-redshift supernovae, Perlmutter *et al.*<sup>11</sup> found a non-zero positive cosmological constant with probability larger than 99% (0.9979 in their primary fit). In order to determine  $\Omega_\Lambda$  and  $\Omega_m$  separately, one would wish to combine this result with that of a complementary technique sensitive to a different linear combination of the two quantities. In fact, an almost orthogonal linear combination is provided by the position of the first acoustic peak in the multipole expansion of the CMBR anisotropy, which depends on the total energy density of the Universe,  $\Omega = \Omega_\Lambda + \Omega_m$  (see below). Data already show that this sum is not very different from one. The crossing of  $\Omega_\Lambda - \Omega_m \simeq 0.5$  and  $\Omega_\Lambda + \Omega_m \simeq 1$ , suggests the values  $\Omega_m \simeq 0.3$  and  $\Omega_\Lambda \simeq 0.7$  (which would saturate an earlier upper bound  $\Omega_\Lambda < 0.7$  obtained for a flat Universe from the frequency of gravitational lensing of quasars<sup>14</sup>). In a few years, with better data,  $\Omega_m$  and  $\Omega_\Lambda$  will be determined in this way to within 10%. The satellite MAP, will be launched by NASA in the year 2000 to measure the anisotropy of the CMBR (a European satellite, the Planck Surveyor, is expected for 2007).

The CMBR provides a snapshot of the Universe at the moment of recombination,  $t_{rec} \simeq 3 \times 10^5$  y, when atoms first became a stable. Photons, which had a very short mean free path in the ionized matter before recom-

bination, interact for the last time and reach us from that “surface of last scattering”. This radiation has the best black-body spectrum in the Universe with deviation of less than 0.005% and a temperature  $T = 2.7277^\circ\text{K}$  measured by the COBE (Cosmic Background Explorer) Satellite<sup>15</sup>. This radiation is remarkably isotropic. Anisotropies are due to our motion with respect to the CMBR rest frame (which generates a dipole anisotropy) and due to the density inhomogeneities that triggered structure formation in the Universe. Results from COBE and other experiments in balloons show temperature anisotropies  $(\delta T/T) \equiv (T - \bar{T})/\bar{T} < 10^{-4}$ , where  $\bar{T}$  is the average temperature (given above). Once within the horizon, the primordial density perturbations (in dark matter) set up sound or acoustic oscillations in the fluid formed by photons, electrons and baryons before recombination. In the surface of last scattering the peaks of compression and rarefaction (for scales that are caught at extrema of their oscillations) are seen as hot and cold spots respectively, both of which appear as peaks in the multipole expansion of the power spectrum of CMBR anisotropies. The horizon size at recombination corresponds to an angle  $\theta_H \simeq 1^\circ\sqrt{\Omega}$  in the present sky. This apparent angular size depends on the geometry of the Universe: it is larger for a closed Universe ( $\Omega > 1$ ) and smaller in an open one ( $\Omega < 1$ )<sup>16</sup>. In multipole number  $\ell \simeq 200^\circ/\theta$ , the position of the horizon is at  $\ell_H \simeq (200/\sqrt{\Omega})$ . Angles larger than  $\theta_H$ ,  $\ell < \ell_H$ , correspond to causally disconnected regions at the time of emission of the CMBR photons, where no acoustic oscillations could have been set. Only values  $\ell \geq \ell_H$  correspond to scales within the horizon. Thus the position of the first acoustic peak (a compression peak) should happen at  $\ell_H$ , which depends on  $\Omega$ . Present data on anisotropies, even if not conclusive, show the first peak at  $\ell$ 's not much lower than 100 or higher than 300.

### 3 Cosmic Energy Densities

Maybe the most important cosmological constraint on stable neutrinos is the mass bound coming from their cosmic energy density. In the same way we have a cosmic background of photons, we expect the existence of a yet never seen cosmic background of relic neutrinos. Knowing so well the CMBR temperature, we know with great accuracy the number and energy density of the CMBR photons which are the most abundant in the Universe by several orders of magnitude,  $n_\gamma = 2\zeta(3)T^3/\pi^2 = 412/\text{cm}^3$ ,  $\rho_\gamma = \pi^2T^4/15 = 4.71 \times 10^{-34} \text{ (g/cm}^3\text{)}$ . We can compute the expected abundance of neutrinos relative to photons. For light standard neutrinos (of mass  $m_\nu < 1 \text{ MeV}$  and no lepton number asymmetry)  $n_{\nu_i} + n_{\bar{\nu}_i} = (3/11)n_\gamma = 112/\text{cm}^3$  (including both neutrinos and antineutrinos in equal numbers) for each light neutrino species. The temperature of neutrinos is

lower than that of photons  $T_\nu = (4/11)^{1/3}T = 1.9^\circ\text{K} = 1.6 \cdot 10^{-4} \text{ eV}$ . Knowing  $T_\nu$ , we can compute the contribution of each relativistic  $\nu$ -species to the present radiation energy, usually parametrized as  $\rho_{\text{rad}} = (\pi^2/30) g_*(T) T^4$ , where  $g_*(T)$  is the effective number of relativistic degrees of freedom. Every standard neutrino species (with no lepton number asymmetry) adds 0.454 to  $g^*$ , while photons contribute with 2. Photons and three relativistic neutrino species add up to  $g_* = 3.362$  and  $\Omega_{\text{rad}} h^2 \simeq 4 \times 10^{-5} (g_*/3.36)$ . If one or more standard neutrino species are non-relativistic at present ( $m_{\nu_i} > T_\nu$ ), then their contribution to the present density of the Universe is  $\rho_\nu = \sum_i m_{\nu_i} (n_{\nu_i} + n_{\bar{\nu}_i}) = \Omega_\nu \rho_c$ , thus

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{92 \text{ eV}}. \quad (1)$$

Only left-handed (non-relativistic) neutrinos (with no lepton number asymmetry) are considered here (for Dirac neutrino masses  $< 1 \text{ keV}$  this is correct, because the contribution of the right-handed states is negligible). If  $m_{\nu_i} = 0.4 h \text{ eV}$  ( $0.3 \text{ eV}$  with  $h = 0.65$ ) standard neutrinos would be as abundant as luminous matter, namely the matter associated with typical stellar populations, which is  $\Omega_{\text{lum}} \simeq 0.004 h^{-1}$  ( $0.6 \cdot 10^{-2}$  for  $h = 0.65$ ). This matter is baryonic, but Big Bang Nucleosynthesis (BBNS) arguments imply that the total density of baryons,  $\Omega_B$ , is larger. Estimates based on the sole density of  $D^{17}$ , whose primordial abundance is the best known among the light elements<sup>18</sup>, give  $\Omega_B = (0.019 \pm 0.0024) h^{-2}$ , comparable to the density of a standard  $2 \text{ eV}$  neutrino. Due to uncertainties in the observational upper bound on the abundance  $^4\text{He}$ , only  $D$  is used to obtain this range. Also due to this uncertainty the limit on  $N_\nu$ , the number of equivalent standard neutrino species in equilibrium during NS, is uncler. At present there are two estimates of primordial  $^4\text{He}$ . The lowest one,<sup>19</sup> together with data on  $D$  would require  $N_\nu < 3$ , while the higher<sup>20</sup>, with a prior  $N_\nu > 3$ , implies  $N_\nu < 3.2$  (95% C.L.)<sup>17</sup>.

The gravitationally dominant mass component of the Universe is “dark”, i.e. it is not seen either in emission or absorption of any type of electromagnetic radiation. This is the dark matter (DM). Recent measurements give  $\Omega_{\text{DM}} > 0.15$  (an absolute lower bound, coming from satellites of spiral galaxies),  $\Omega_{\text{DM}} = (0.19 \pm 0.06) \text{ B}$  (with  $\text{B} \simeq 1$ , from the mass over light ratio of clusters),  $\Omega_{\text{DM}} = 0.44 \pm 0.11$  (from the baryon fraction in clusters, using BBNS),  $\Omega_{\text{DM}} \simeq 0.55 \pm 0.17$  (from the abundance of high- $z$  clusters). Notice that none of these dynamical estimates reaches 1. Important for neutrinos is a bound that depends on the total density of DM, coming from structure formation arguments (presented in the following section), that say that most of the DM in the Universe should be cold (i.e. non relativistic at temperatures of about  $T \simeq 1 \text{ keV}$ , when galaxies should start forming), called CDM,

and only a small amount could be hot (i.e. relativistic at  $T \simeq 1$  keV, such as light neutrinos), called HDM. This bound is  $\Omega_\nu \leq (0.2 - 0.3)\Omega_m$ , where  $\Omega_m \simeq \Omega_{DM} = \Omega_{CDM} + \Omega_\nu$ . With  $\Omega_m = 1$ ,  $\Omega_\nu \leq 0.2$  gives an often quoted bound  $\sum_i m_{\nu_i} \leq 5$  eV, for  $h = 0.5$  (this low value of  $h$  is necessary in a flat matter dominated Universe to account for the age of the Universe, as mentioned above). However, lower values of  $\Omega_{DM}$ , as measurements seen now to point to, would lead to more stringent bounds on  $\Omega_\nu$ .

We have spoken so far about neutrinos with no or negligible lepton number asymmetry. However lepton asymmetries in neutrinos may be large (see the end of Sec. 4).

#### 4 Structure Formation of the Universe.

The Universe looks lumpy at scales  $\lambda \simeq 100$  Mpc, we see galaxies, clusters, superclusters, voids, walls. But it was very smooth at the surface of last scattering of the CMBR and later. Inhomogeneities have been seen as anisotropies in the CMBR, so the density contrast  $\delta\rho/\rho \equiv (\rho(x) - \rho)/\rho$  (where  $\rho$  is the average density) cannot be much larger than  $\delta T/T \simeq 10^{-4}$ . So inhomogeneities in density start small and grow through the Jeans (or gravitational) instability; gravitation tends to further empty underdense regions and to further increase the density of overdense regions. One can follow analytically the evolution due to gravity of the density contrast in the linear regime, where  $\delta\rho/\rho < 1$ . In a static fluid the rate of growth of  $\delta\rho/\rho$  is exponential, but in the Universe (an expanding fluid) it slows down into either a power law,  $\delta\rho/\rho \sim a(t)$ , in a matter dominated Universe, or it stops,  $\delta\rho/\rho \simeq \text{constant}$ , in a radiation or a curvature dominated Universe (a matter dominated open Universe becomes curvature dominated for  $a(t) \geq \Omega_o/(1 - \Omega_o)$ ). Here  $a(t)$  is the scale factor of the Universe, which accounts for the Hubble expansion of the linear dimensions of the Universe. Perturbations have different physical linear dimensions  $\lambda = a(t)\lambda_{\text{com}}$ , where  $\lambda_{\text{com}}$  are linear dimensions measured in comoving coordinates (those that expand with the Hubble flow). With the usual choice of  $a = 1$  at present,  $\lambda_{\text{com}}$  are the present actual linear dimensions. Since  $a \sim t^\alpha$  with  $\alpha < 1$  while the horizon  $ct$  grows linearly with  $t$ , the horizon increases with time even in comoving coordinates, encompassing more material as time goes. When  $\lambda = ct$  we say the perturbation of size  $\lambda$  “enters” into the horizon, we could better say the perturbation is first encompassed by the horizon. This moment is called “horizon-crossing” and it happens at different times for different linear scales  $\lambda$ , larger scales cross later.

Independently of the origin of the primordial fluctuation, it is convenient to specify the spectrum of fluctuations at horizon-crossing,  $(\delta\rho/\rho)_{\text{hor}}$ . A spectrum

scale invariant at horizon-crossing, namely with  $(\delta\rho/\rho)_{\text{hor}} = \text{constant}$ , is called a Harrison-Zel'dovich spectrum. COBE observations have shown the spectrum at horizon-crossing is in fact scale invariant or very close to it.

After horizon-crossing, physical interactions act upon the inhomogeneities and generate a “processed” spectrum, which determines which structures are formed first. This question leads to the distinction of three types of DM: hot (HDM), warm and cold (CDM) (i.e. relativistic, becoming non-relativistic and non-relativistic at temperatures of order keV).

Simulations have shown that CDM must be the most abundant form of matter, because the “processed” spectrum of perturbations generated in standard CDM models reproduces the observations within 10%. Standard CDM models, make the simplest assumptions, namely  $\Omega_{\text{CDM}} + \Omega_{\text{B}} \simeq \Omega_o = 1$ ,  $\Lambda = 0$ , scale invariant perturbations at horizon crossing, and a scale independent “biasing” by which only the highest peaks in the CDM density distribution end up forming galaxies. There is only one feature in the processed spectrum of CDM perturbations, a change of slope at the present scale that corresponds to the horizon at the moment of matter-radiation equality,  $\lambda_{\text{eq}}$ . The Universe is matter dominated at present, but due to the different evolution with temperature  $T$  of the density of matter and radiation,  $\rho_{\text{m}} \sim T^3$ ,  $\rho_{\text{r}} \sim T^4$ , the radiation was dominant in the past, at  $T > T_{\text{eq}}$ , where  $T_{\text{eq}}$  is the temperature of matter-radiation equality  $\rho_{\text{r}}(T_{\text{eq}}) = \rho_{\text{m}}(T_{\text{eq}})$ ,  $T_{\text{eq}} \simeq 5.8\text{eV}\Omega_o h^2(3.36/g_*)$ .  $\Omega_o$  is the present matter density (neglecting the present small radiation contribution) and  $g_*$  is the number of effective relativistic degrees of freedom ( $g_* = 3.36$  with photons and three relativistic neutrino species). The present physical size of the horizon then is

$$\lambda_{\text{eq}} \simeq 10 \text{ Mpc} \left( \frac{g_*}{3.36} \right)^{1/2} \frac{1}{\Omega_o h^2} . \quad (2)$$

Perturbations with  $\lambda < \lambda_{\text{eq}}$  enter into the horizon at  $t < t_{\text{eq}}$ , when the Universe is radiation dominated. They cannot grow while the Universe is radiation dominated, so they all start growing together at  $t = t_{\text{eq}}$  and they roughly have the same amplitude today, if they all start with the same amplitude at horizon crossing. Perturbations with  $\lambda > \lambda_{\text{eq}}$ , instead, enter into the horizon at  $t > t_{\text{eq}}$ , when the Universe is matter dominated, and, thus, start growing immediately. Consequently, perturbations at larger scales enter later, have less time to grow and their amplitude is smaller at present. Once  $\lambda_{\text{eq}}$  (the location of the change slope) is fixed, the only remaining free parameter in the processed spectrum of CDM is an overall normalization, provided by the CMBR anisotropy measured by COBE at large scales,  $\theta > 20^\circ$ . Density perturbations at these large scales entered into the horizon very recently (so they did

not grow much), thus providing a measurement of  $(\delta\rho/\rho)$  at horizon crossing,  $(\delta\rho/\rho)_{\text{hor}}$  (for more details, see e.g. Ref. 21).

While both the shape and normalization so obtained are almost right, they do not fit the observations<sup>22</sup>. The spectrum of standard CDM models has too much power on small scales (large  $k \sim \lambda^{-1}$ ), the scales of galaxy clusters and smaller.

Once the normalization given by COBE is fixed, there are several possibilities to change the spectrum to agree with observations. Because HDM tends to erase structure at small scales (while neutrinos are relativistic) one of the solutions consists in adding to the CDM a bit of HDM, namely neutrinos, in what are called mixed DM (MDM) or hot-cold DM (HCDM) models<sup>23</sup>. In particular, models with  $\Omega_\nu = 0.2$ , what corresponds to  $\sum_i m_{\nu_i} = 5$  eV, and the rest of  $\Omega_o$  in CDM plus some baryons, with  $\Omega = 1$ ,  $\Lambda = 0$  and a scale invariant spectrum of fluctuations at horizon crossing work well. However other possible variations of the standard CDM models also work well to fit the LSS data, for example that of a “tilted” primordial spectrum of fluctuations at horizon crossing, one that slightly favors larger scales over smaller scales (instead of the flat, scale invariant, Harrison-Zel’dovich spectrum) within the COBE observational limits. This is called “tilted” CDM (TCDM).<sup>24</sup> A mixed model with both some neutrinos and some “tilt” also does work, and in these models  $\Omega_\nu < 0.2$  (see, for example,<sup>25</sup>).

Another family of solutions is obtained by realizing that a shift towards larger scales of the only feature in the CDM spectrum, i.e.  $\lambda_{\text{eq}}$ , given in Eq. (2), the scale where the slope in the spectrum changes, is enough to provide good agreement with observations, since it effectively amounts to increasing the power of the spectrum at scales larger than the break point ( $\lambda > \lambda_{\text{eq}}$ ) with respect to those smaller than it ( $\lambda < \lambda_{\text{eq}}$ ). Using Eq. (2) the relation  $\lambda_{\text{eq}} \equiv (10h^{-1}M_{\text{pc}})\Gamma^{-1}$  defines the “shape parameter”<sup>26</sup>  $\Gamma \equiv \Omega_o h (g_*/3.36)^{-1/2}$ . The LSS data require  $\Gamma \simeq 0.25 \pm 0.05$ , while standard CDM models (with the standard choices of  $h = 0.5$ ,  $\Omega_o = 1$ ,  $g_* = 3.36$ ) has  $\Gamma = 0.05$ . In fact, as we have explained, a larger  $\lambda_{\text{eq}}$ , thus a smaller  $\Gamma$ , would provide agreement with data. In order to lower the value of  $\Gamma$  with respect to that of the standard CDM model one needs to either, 1): lower  $h$ ,  $h < 0.5$ <sup>27</sup> (what implies an older Universe and is very unlikely given the present determinations of  $h$ ), or 2): increase  $g_*$  (namely increase the radiation content of the Universe at  $t_{\text{eq}}$ ), or 3): lower  $\Omega_o$  (i.e. take  $\Omega_o < 1$ ), so that we either live in an open Universe (open CDM models, OCDM) if  $\Lambda = 0$  or in a Universe with a cosmological constant that provides  $\Omega_{\text{vac}} = 1 - \Omega_o$  ( $\Lambda$ CDM models<sup>28</sup>), or 4): a combination of all three above.

A way of obtaining the large amount of radiation needed for the second

possibility is through a heavy neutrino decaying into relativistic particles, i.e. radiation, with the right combination of mass and lifetime, in so-called  $\tau$ CDM models<sup>29 30</sup>. A massive neutrino matter dominates the energy density of the Universe as soon as it becomes non-relativistic, i.e. as soon as  $m_\nu \geq T$  (since  $n_\nu \simeq n_\gamma$  and  $\rho_\nu = n_\nu m_\nu$ ,  $\rho_{\text{rad}} \simeq n_\gamma T$ ), thus their decay products radiation-dominate the Universe at decay. For  $m_\nu < 1$  MeV standard neutrinos the right mass-lifetime combination lie on a narrow strip around the previously mentioned “galaxy formation” bound<sup>31</sup>. Near this bound, at the boundary between being irrelevant and harmful, unstable neutrinos could help in the formation of structure in the Universe<sup>29</sup>. A heavier neutrino, of  $m_\nu \simeq 1 - 10$  MeV, necessarily  $\nu_\tau$ , decaying at or just before nucleosynthesis,  $\tau = 0.1 - 100$  sec, would also provide a solution<sup>30</sup>. The  $\nu_\tau$  decay modes involved here should all be into neutral particles,  $\nu_\tau \rightarrow 3 \nu$ 's or  $\nu_\tau \rightarrow \nu\phi$ , with  $\phi$  a Majoron (a zero mass Goldstone boson) for example. All visible modes, i.e. producing electrons or photons, are forbidden in the necessary range.

Radiation-matter equality may also be delayed by the existence of large lepton asymmetries in neutrinos, so that these may be more abundant than photons<sup>32</sup>,  $(n_\nu/n_\gamma) > 1$  (and dominate the entropy  $s$  of the Universe,  $n_\nu/s = O(1)$ ). Relic neutrinos this abundant would be Fermi-degenerate, since their chemical potential  $\mu_\nu$  would be larger than their temperature. Let us recall that, while charge neutrality imposes a lepton number asymmetry in electrons as large as the baryon asymmetry in protons, i.e.  $(n_e - n_{\bar{e}})/n_\gamma \simeq 10^{-10}$ , no such restrictive bound operates on neutrinos. We will return below to this very recently explored possibility, that we call LCDM (for CDM with large lepton asymmetry L).

All these modified CDM models seem to be able to fit present large scale structure data, however they predict very different patterns of acoustic peaks in the CMBR anisotropy power spectrum, and already present data on this anisotropy allow to constrain the models. All recent analyzes perform a combined fit to LSS and CMBR anisotropy data. CHDM<sup>33</sup>,  $\tau$ CDM<sup>34</sup>, and LCDM<sup>32</sup> have been favorably compared with others in their ability to fit LSS and CMBR data.

Gawiser and Silk<sup>33</sup> claimed that CHDM with 5 eV total neutrino mass ( $\Omega_\nu = 0.2$ ,  $\Omega_m = 1$ ,  $\Omega_\Lambda = 0$ ,  $h = 0.5$ ) gives the best fit among all the 10 models they studied. However, they mention that this model, as all others with  $\Omega = \Omega_0 = 1$  (flat matter dominated Universe) may not account for the recent evidence for early galaxy formation. In fact, evidence has been found for the existence of a large amount of bright galaxies rather early, at redshifts  $z \simeq 3$ , and Somerville, Primack and Faber<sup>35</sup> concluded that no  $\Omega = \Omega_0 = 1$  model with a realistic power spectrum makes anywhere near enough of them. This can

be understood by recalling that in a matter-dominated universe  $(\delta\rho/\rho)$  grows as the scale factor while in a curvature or  $\Lambda$ -dominated universe the growth of  $(\delta\rho/\rho)$  stops. Thus, in order to get to the same present level of structure, the density contrast of perturbations  $(\delta\rho/\rho)$  should be bigger at early times in the later case (growth of  $(\delta\rho/\rho)$  stops at some point in the past) than in the former (in which the growth of  $(\delta\rho/\rho)$  continues until now). Based on these considerations, as well as on the Type Ia SN data, which favor  $\Lambda > 0$ , Primack and Gross<sup>36</sup> studied the combined fit to LSS and CMBR data of a  $\Lambda$ CHDM model, namely flat models with  $\Omega_m < 1$  and  $\Omega_\Lambda = 1 - \Omega_m$ , and with some HDM in neutrinos. They found the best fits had  $\Omega_m = 0.5$  (0.6) with  $(\Omega_\nu/\Omega_m) = 0.1$  (0.2) (namely  $\Omega_\nu = 0.05$  (0.12)) corresponding to  $\sum_i m_{\nu_i} = 1.6$ (4) eV (since they used  $h = 0.6$ ). They found that the addition of HDM does not change a  $\Lambda$ CDM model by much, contrary to the substantial improvement this addition provided to standard CDM models. However, they also concluded that  $\Lambda$ CDM and also  $\Lambda$ CHDM models provide a relatively poor fit to the LSS data (to the power spectrum near the peak), what is also mentioned in Ref. 33. The new large scale surveys under way (2dF and SDSS) will be crucial in determining the viability of these models.

Light neutrinos not being a necessary addition to the matter composition of the Universe to explain the known data, the studies just mentioned provide an upper bound (already mentioned in Section 3) on the relative amount of neutrinos with respect to CDM: in all of them  $\Omega_\nu/\Omega_m \leq 0.2 - 0.3$ .

Let us finally return to the possibility of relic neutrinos with a large lepton asymmetry. Adams and Sarkar<sup>32</sup> found that a relic neutrino species with chemical potential  $\mu_\nu = 3.4 T_\nu$  added to a standard CDM model (flat matter dominated universe) provides a good fit to the LSS and CMBR data. The best bounds on large  $\mu_\nu$  come from BBNS (which becomes severely non-standard in the presence of large neutrino asymmetries) and structure formation. Relic neutrinos with large chemical potentials  $\mu_\nu > T$ , would form a Fermi degenerate background with number density  $n_\nu = (12\zeta(3))^{-1} (T_\nu/T_\gamma)^3 [\pi^2[(\mu_\nu/T) + (\mu_\nu/T)^3] = 0.0252[9.87(\mu_\nu/T) + (\mu_\nu/T)^3]$ , where  $(T_\nu/T_\gamma)^3$  has the standard value of  $(4/11)$  for  $(\mu_\nu/T) < 12$ . For  $\mu/T = 3.4$ , the density of neutrinos would be  $n_\nu = 1.8 n_\gamma = 756/\text{cm}^3$ . Parenthetically let us point out that slightly larger chemical potentials, still allowed by LLS and CMBR data, could make neutrinos with the mass implied by SuperKamiokande data, in the case of hierarchial masses,  $m_\nu = \sqrt{\delta m^2} \simeq 0.07$  eV, a relevant HDM component. For example with  $(\mu_\nu/T) = 4.6$ , the relic neutrino density would be  $n_\nu = 3.6 n_\gamma$  and a neutrino of mass 0.7 eV would have  $\Omega_\nu h^2 = 0.01$ .<sup>37</sup> These neutrinos would still be relativistic at the moment of radiation-matter equality, so they would have on structure formation almost the same effect as the massless neutrinos studied by

Adams and Sarkar. The large neutrino asymmetries necessary in these models could possibly be generated through neutrino oscillations after the electroweak phase transition (this needs to be studied) and certainly with the Affleck-Dyne mechanism.<sup>38</sup>

Many possibilities are still open, but the quality data necessary to discriminate among models are coming, and a confirmation of one of them may be possible within a few to ten years. Besides getting to know  $\Omega$ ,  $\Omega_B$ ,  $\Omega_\Lambda$ ,  $\Omega_m$ ,  $H$ ,  $t_o$  etc., the relevant cosmological parameters to a few %, standard neutrinos with no lepton asymmetry will be seen either as HDM for  $m_\nu \geq 1$  eV (may be up to 0.3 with low  $\Omega_m$ )<sup>39</sup> or for lighter neutrinos, the number of neutrino species will be determined with precision similar to the NS bounds.<sup>40</sup> The case of large neutrino lepton asymmetry has yet to be studied.

## 5 Astrophysics.

Neutrinos may have an important role in the evolution of some types of stars, in particular in the explosion of Type II SN. These are stars in which the Fe-core reaches the Chandrasekar limit and, thus, collapses into a neutron star, trapping the emitted neutrinos for several seconds within a region called “neutrino-sphere”, and exploding the mantle of the star. Actually the neutrino spheres of different neutrinos types are slightly different leading to different neutrino average energies. Most of the binding energy of the remaining neutron star goes into neutrinos. Thus, the explosion mechanism is sensitive to non-standard neutrino properties. Some examples are the following.

A problem in Type II SN modelling is that the shock wave which should explode the mantle stalls before getting to do it. This problem might be solved if the  $\nu_e$  arriving at the shock from the  $\nu$ -sphere are actually  $\nu_\mu$  or  $\nu_\tau$  which oscillated resonantly into  $\nu_e$  on their way.<sup>41</sup> These  $\nu_e$  arriving at the shock would have the higher energy of the originally emitted  $\nu_\mu$ - $\nu_\tau$ , 24-27 MeV, instead of the lower energy of 10-12 MeV with which  $\nu_e$ 's are emitted, leading to a more efficient energy transfer to the shock. This would require  $\Delta m^2 = 10^2$  to  $10^4 \text{eV}^2$  and mixing angles  $\sin^2(2\theta) > 10^{-7}$  approximately. However, these resonant oscillations may prevent the r-process (rapid neutron capture) synthesis of heavy elements, whose preferred site is behind the shock wave of an exploding Type II SN. Because the energy of  $\nu_e$  in this case would be larger than that of  $\bar{\nu}_e$ , 14-17 MeV, the environment would become proton rich, while r-process requires a neutron rich medium.<sup>42</sup> This would happen for  $\Delta m^2 = 10$  to  $10^4 \text{eV}^2$  and mixing angles  $\sin^2(2\theta) > 10^{-6}$  approximately. The matter enhanced oscillations of  $\nu_e$  and a sterile neutrino may instead help r-process, by eliminating the  $\nu_e$  which decimate neutrons (through the reaction

$n\nu_e \rightarrow pe^-$ )<sup>43</sup>, for  $\Delta m^2 = 1$  to  $10^2 \text{eV}^2$  and mixing angles  $\sin^2(2\theta) > 10^{-3}$  approximately. These arguments involving r-process in Type II SN are to be taken with a grain of salt, considering that there is another possible site for it, in binary neutron star - neutron star mergers.

As the last point, let us mention “pulsar kicks”. Pulsars, which are neutron stars with large magnetic fields, are not confined to the disk of our galaxy, where they must have been born, but move in all directions with large velocities of 500 km/sec on average. A “pulsar kick” which may impart these velocities may result from the existence of a matter-enhanced resonant region between the more internal  $\nu_\mu, \nu_\tau$  and the more external  $\nu_e$  neutrino spheres.<sup>44</sup> Along the direction of the magnetic field the resonance happens at larger densities, thus more internally in the protostar.<sup>45</sup> The  $\nu_e$  oscillated into  $\nu_\mu$  or  $\nu_\tau$  within the  $\nu_e$  sphere (from which they could not escape otherwise) but outside the  $\nu_\mu, \nu_\tau$  sphere can freely escape, and they carry more energy away when the conversion happens the farthest from the surface of the star (where temperatures are higher). Thus, the deformation of the resonance region due to the presence of a large magnetic field, has as a consequence the emission of hotter converted  $\nu_e$  neutrinos in the direction of the magnetic field and cooler ones in the opposite direction. A 1% asymmetry in the total momentum carried by the emitted neutrinos would be enough to impart to the remaining neutron star the large velocities of pulsars.<sup>44</sup> Several versions of this mechanism have been proposed.<sup>46</sup>

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